CHAPTER 11

CRITERIA

11-1. Static.

a. Selection of Loading Combinations. Tables 4-1 and 4-2 presented the static and dynamic loading combinations to be used for designing arch dams. The load cases covered in these tables should be sufficient to cover most arch dams; however, the structural designer should closely examine each load case to ensure that it is applicable to his/her project and that it is properly classified under one of the three categories, i.e., Usual, Unusual, and Extreme. For example, loading combination SUN1 in Table 4-1 may be more appropriate under the Usual loading combinations for a hydropower dam since the reservoir level is more likely to be maintained routinely at or near the spillway crest. The same situation may apply to the load case SUN3 for a flood control dam. Again, this case would be more appropriate as a Usual condition for a single purpose, flood control dam if a dry reservoir is normally to be maintained. The loading combinations should be established at the earliest stages of design and adhered to throughout the development of the final design. Since there are different allowables and FS's for different groups of loading combinations, the selection and classification of load cases greatly influence the geometry of an arch dam and the resulting stresses.

b. Allowables and Factors of Safety - Static Loading. The allowable stresses and FS's for static loading combinations are given in Table 11-1. Arch dams should be designed using a minimum concrete compressive strength, f'_c, of 4,000 psi. In most cases, a single concrete mix with an f'_c of 4,000 psi would be sufficient for the entire dam; however, the final selection of the concrete strength would have to be based on the requirements of the stress analysis. Where the results of the stress analysis indicate the need for higher allowables than what a 4,000 psi concrete produces, it may be possible to use more than one design strength concrete in the dam, i.e., a concrete mix with an f'_c of 4,000 psi for most of the dam and a higher-strength concrete only for the localized areas which require the higher allowables. For large dams, it may be economically advantageous to use higher-strength concrete in areas where stresses exceed the allowables for the 4,000 psi concrete, rather than using a single higher-strength concrete for the entire dam. Tensile strength of the concrete, f'_t, is based on the results of the splitting tensile tests for the mix design being considered for the dam. In the absence of test results and for preliminary design purpose, a value for f'_t equal to 10 percent of the compressive strength may be used. This value is based on extensive testing performed for the Portugues Dam (USAED, Jacksonville, 1988a) and is consistent with work done by Raphael (1984). The sliding FS's shown in Table 11-1 are based on a comprehensive field investigation and testing program as described in Chapter 10.

c. Stability of Cantilevers During Construction. Arch dams are constructed in monoliths in the same manner as a gravity dam. Because of the vertical curvature, the monoliths of an arch dam may be unstable against overturning prior to the grouting of the monolith joints and the raising of the reservoir. The stability of the cantilevers must be checked during early

TABLE 11-1

Static Loading Combinations

Allowables and Factors of Safety

f'_c = Compressive strength ≥ 4,000 psi
f'_t = Tensile strength
f_c = Allowable compressive stress
f_t = Allowable tensile stress
FS_s = Factor of safety against sliding

Static Usual

$f_c = f'_c/4$	$f_t = f'_t$	$FS_s = 2.0$

Static Unusual

$f_c = f'_c/2.5$	$f_t = f'_t$	$FS_s = 1.3$

Static Extreme

$f_c = f'_c/1.5$	$f_t = f'_t$	$FS_s = 1.1$

Construction Condition (before grouting)

Resultant location within base, $f_t = f'_t$

stages of the design layout to assure that each cantilever is stable at different stages of concrete placement. Table 11-1 contains a construction condition load case with $f_t = f'_t$. This allowable is permitted only if the concrete has aged sufficiently - normally a 1-year strength is specified - to gain its design strength. This is generally not a concern since the cantilevers experience this level of tensile stresses after they have been topped off, and at this time the specified strength age has elapsed for the lower lifts where the high tensile stresses are likely to occur. As a general rule, tensile stresses should not be allowed to reach this limit since other loading combinations would more than likely worsen this condition. Cantilever stability may not be a problem if reservoir filling is concurrent with the construction of the dam.

d. Tensile Stresses.

(1) General. Tensile stresses are inherent to most double-curvature arch dams and require further discussion. As seen in Table 11-1, the allowable tensile stress is equal to the tensile strength of concrete which indicates an FS of unity. However, the intent of any design is to minimize or limit tensile stresses to localized areas by reshaping and/or redesigning the dam to the extent possible as discussed in Chapter 6, paragraph 6-6. A dam designed with high tensile stresses - though within the allowable - in too many areas would more than likely exceed the compressive allowables under one or more loading combinations. The allowables in Table 11-1 are established

based on the failure mode of arch dams. When the tensile strength of the concrete is exceeded and cracking occurs, the uncracked portion of the cantilever would tend to carry more compression and the balance of the loads would have to be carried by the arches. If the cracking due to tension becomes widespread, too much of the load will have to be carried by the arches. The uncracked portion of the cantilevers, in turn, can exceed the compressive strength of the concrete and cause crushing failure of the concrete (unless the foundation has failed first). Therefore, since compression is the mode of failure of an arch dam, a more conservative approach is taken in establishing the allowable compressive stresses, as seen Table 11-1.

(2) Design Guidelines. As discussed in the previous paragraph, one of the objectives in arch dam design is minimizing the magnitude and the locations of tension in the dam. Most arch dams exhibit tensile stresses at the downstream face of the cantilevers along the foundation under the low reservoir-high temperature condition and during - or at the end of - construction. Although attempts should be made to improve the stresses as much as possible, this condition should not be regarded as a significant problem as long as the stability of the cantilevers is not in question, as discussed in paragraph 11-1c. Tensile stresses at the downstream face of cantilevers are relieved - to a varying degree - when the reservoir level rises. Even if some cracking has occurred, the additional hydrostatic load and the resulting downstream deflection will cause the cracks to close. Tension at the upstream face of the dam should be given a more careful consideration. The primary reason for the concern is the possibility of a seepage path through the dam if cracks were to develop and extend through the thickness of the dam. It should be stated that cracked cantilevers do not imply a dam failure. Loads previously carried by cantilevers before cracking will be transferred to the arches and other cantilevers. A cracked cantilever analysis should be performed to ensure the compressive stresses of the remaining uncracked section and the other arches and cantilevers remain within the allowable concrete stresses. This type of analysis may be performed using the computer program ADSAS (USBR 1975 and USAEWES, instruction report, in preparation) or, if needed, a more refined FEM analysis. As mentioned earlier, tension is not the mode of failure in an arch dam. The reason for the elaborate treatment of this subject is that reducing tensile stresses to the acceptable level in arch dams is the most difficult step in the layout and design procedure.

11-2. Dynamic.

a. Allowables and FS Safety - Dynamic Loading. Establishing the acceptability of performance of arch dams under dynamic load cases is a complicated process which cannot be summarized in a table as was done in Table 11-1 for the static condition. The allowables given in the following table are only the first step in determining the safety criteria and should not be regarded as absolute limits. Additional discussion on this subject is presented later in this chapter. In Table 11-2, f'_{cd} and f'_{td} are based on the test results for the appropriate rate of loading as indicated by the dynamic analysis. If the laboratory testing is done before the results of the dynamic analysis are available, several rates of loading may be used to develop a curve for future use. A range of failure times between 20 msec and 150 msec should provide sufficient test data to cover most cases. The dynamic tensile strength, f'_{td}, in Table 11-2 is based on the modulus of rupture test for the

TABLE 11-2

Dynamic Loading Combinations

Allowables and Factors of Safety

f'_{cd} = Dynamic compressive strength
f'_{td} = Dynamic tensile strength
f_c = Allowable compressive stress
f_t = Allowable tensile stress
FS_s = Factor of Safety against sliding

Dynamic Unusual

$f_c = f'_{cd}/2.5$	$f_t = f'_{td}$	$FS_s = 1.3$

Dynamic Extreme

$f_c = f'_{cd}/1.5$	$f_t = f'_{td}$	$FS = 1.1$

the concrete used in the dam, as modified according to the approach discussed by Raphael (1984). The sliding FS in Table 11-2 are based on a comprehensive field investigation and testing program as described in Chapter 10.

b. Acceptability of Performance. The dynamic load cases to be used in the analysis of arch dams were given in Table 4-2. Under load case DUN1, OBE + Normal Operating Reservoir Condition, the stresses in the dam must remain totally within the elastic range of concrete, assuming the dam behaves as a monolithic structure. For the end of construction condition, load case DUN2, localized inelastic behavior will be allowed; however, no condition leading to the impairment of operation will be permitted. In the case of the MDE loading, i.e., load case DE1, nonlinear, inelastic behavior will be allowed while maintaining the structural integrity of the dam. This means that no conditions leading to the uncontrolled release of water will be permitted. However, in cases where the ground motions due to OBE approach the MDE's ground motions, some inelastic behavior is allowed in localized areas of the dam.

c. Dynamic Response of Arch Dams. The extraordinary strength of arch dams has been recognized for centuries, a fact attested by some of the oldest masonry structures still standing in the Middle East. According to records to date, there has been no structural failure of an arch dam due to an earthquake. However, some of the modern dams, i.e., the ones constructed in the 1900's, will probably show signs of distress if analyzed using state-of-the-art methods of analysis, even though some of these dams have experienced severe earthquakes without suffering any structural damages. Depending on the intensity of the ground motions and other pertinent design parameters, an arch dam would typically exhibit high tensile stresses in the arch (horizontal) direction in the upper part of the dam and in the vertical direction at the base of cantilevers when analyzed using a linear FEM. Considering the fact that in reality the dam is constructed in monoliths which are separated from each other by vertical contraction joints, the indicated horizontal tensile stresses as determined from a linear analysis, will be redistributed since contraction joints are not capable of transferring tension. The magnitude of the real tensile stresses depend largely on the spacing of monolith joints. It is anticipated that longer monoliths would develop larger horizontal tensile stresses than shorter monoliths.